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FROM: D. H. KNOEBEL DHK

CORRELATION OF SUBCOOLED BURNOUT HEAT FLUX

Attached is a memorandum that presents alternative correlations for the burnout heat flux over the entire subcooling range. This work was done by N. H. Chen (ORAU Research Participant) during the summer of 1968. An analysis of the correlations shows:

1) The derived equations provide a slight improvement in the accuracy of fitting the data over the burnout heat flux correlations presently used probably because of the larger number of constants used. Because the improvement is small and the presently used correlations are easier to use, no change is recommended at present.

2) The results as presented in Equations II and IV of the memorandum are useful to compare expected burnout heat fluxes in D_2O with those observed in water. At a velocity of 30 ft/sec, pressure of 50 psia, and subcooling of 39°C, the calculated burnout heat flux for H_2O is 1.36×10^6 pcu/hr-ft^2-°C. The calculated burnout heat flux for D_2O is 0.88 and 0.21, $\times 10^6$ pcu/hr-ft^2-°C, using equations II and IV, respectively. As indicated by this result, the dependence of the burnout heat flux on the physical properties is not properly defined by the equations proposed herein.

3) The recommended equation (I) is the first attempt at including the low subcooling burnout data in the correlation. Although the correlation predicts the burnout heat flux with reasonable accuracy, the indicated dependency of the burnout heat flux on bulk liquid temperature and relative independence of subcooling would be difficult to justify on the basis of a physical model. The unrealistic physical picture is a result of least squares analysis which requires only that the sum of the squares of the deviations be a minimum. This approach is not recommended as a basis for a theoretical model.

DHK:msw
Attach.

TECHNICAL DIVISION
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January 3, 1969

M E M O R A N D U M

TO: S. MIRSHAK

FROM: N. H. CHEN* NHC/DATE

CORRELATION OF SUBCOOLED BURNOUT HEAT FLUX

INTRODUCTION AND SUMMARY

The experimental subcooled burnout heat flux data from Reference 1 have been correlated by the following six equations:

A. Whole Range (246 Experimental Points)

I. $$Q/A = \frac{3.26\times10^{14}\ V^{0.545}\ P^{1.244}}{\Delta T_S^{0.097}\ T_L^{4.687}}$$

Regression coefficient 0.976

II. $$\frac{Q/A}{V\rho_L\lambda} = \frac{3.94\times10^{14}\left(\frac{\rho_V}{\rho_L}\right)^{1.708}\left(\frac{k\Delta T_S}{VL\rho_L\lambda}\right)^{1.019}}{\left(\frac{PL}{\sigma}\right)^{1.437}\left(\frac{\mu}{VL\rho_L}\right)^{0.567}\left(\frac{C_p\Delta T_S}{\lambda}\right)^{0.674}}$$

Regression coefficient 0.939

B. High Subcooling (206 Experimental Points $\Delta T_S > 25°C$)

III. $$Q/A = \frac{2.62\times10^{4}\ V^{0.533}\ \Delta T_S^{0.709}\ P^{0.138}}{T_L^{0.193}}$$

Regression coefficient 0.976

IV. $$\frac{Q/A}{V\rho_L\lambda} = 4.16\times10^{-3}\left(\frac{PL}{\sigma}\right)^{0.555}\left(\frac{k\Delta T_S}{VL\rho_L\lambda}\right)^{0.016}\left(\frac{\mu}{VL\rho_L}\right)^{0.449}\left(\frac{C_p\Delta T_S}{\lambda}\right)^{0.760}\left(\frac{\rho_L}{\rho_V}\right)^{0.488}$$

Regression coefficient 0.975

*This work was done at SRL by N. H. Chen (Associate Professor at Lowell Technological Institute, Lowell, Mass.) during the summer of 1968 as an ORAU Research Participant.

C. Low Subcooling (40 Experimental Points, ΔT_s <25°C)

V. $$Q/A = \frac{4.78 \times 10^{16}\ V^{0.543}\ P^{1.337}}{\Delta T_s^{0.145}\ T_L^{5.622}}$$

Regression coefficient 0.941

VI. $$\frac{Q/A}{V\rho_L\lambda} = 3.03\times10^{24} \left(\frac{\rho_V}{\rho_L}\right)^{2.840} \left(\frac{k\Delta T_s}{VL\rho_L\lambda}\right)^{0.515} \left(\frac{\sigma}{PL}\right)^{2.368} \left(\frac{VL\rho_L}{\mu}\right)^{0.124} \left(\frac{\lambda}{C_p\Delta T_s}\right)^{0.452}$$

Regression coefficient 0.935

The ranges of variables correlated by these equations are:

Burnout heat flux: 0.60-2.02 (10^6 pcu/hr-ft^2)

Pressure = 25-100.0 psia

Velocity = 12-48 ft/sec

Subcooling = 4-72°F

Length of heater = 24 inches

Equivalent diameter = 0.375 inch

Equation I is recommended because it is much easier to use than Equation II. The correlation plot of this equation is shown in Figure 1.

Method of Approach:

(I) Dimensional Analysis - Because the experimental data were obtained from one configuration, the variables, such as roughness of the surface, physical properties of the surface, etc., can be eliminated. Temporarily, we include only D, equivalent diameter, and L, length of the heater, in the analysis. The variables considered in the dimensional analysis are:

1. Burnout heat flux, Q/A, $[H/\theta L^2]$, Btu/hr-ft^2
2. Pressure, P, $[F/L^2]$, lb$_f$/in^2
3. Velocity, V, $[L/\theta]$, ft/sec
4. Subcooling, ΔT_s, [T], °F
5. Equivalent diameter D, [L], inch

6. Length, L, $[L]$, ft

7. Latent heat of vaporization, λ, $[H/M]$, Btu/lb_m

8. Surface tension of liquid, σ, $[F/L]$, lb_f/ft

9. Specific heat of liquid, C_p, $[H/MT]$, Btu/lb_m-°F

10. Thermal conductivity of liquid, k, $[H/\theta TL]$, Btu/sec-ft-°F

11. Viscosity of liquid, μ, $[M/L\theta]$, lb/ft-sec

12. Density of liquid, ρ_L, $[M/L^3]$, lb_m/ft^3

13. Density of vapor, ρ_V, $[M/L^3]$, lb_m/ft^3

Using the Buckingham π theorem, the above variables are combined to form the following groups:

$$\pi_1 = (Q/A)/(\lambda V \rho_L) \qquad \pi_2 = D/L$$

$$\pi_3 = PL/\sigma \qquad \pi_4 = \rho_V/\rho_L$$

$$\pi_5 = (k\Delta T_S)/(VL\rho_L\lambda) \qquad \pi_6 = \mu/(VL\rho_L)$$

$$\pi_7 = C_p\Delta T_S/\lambda$$

Hence, these dimensionless groups can be correlated by

$$(Q/A)/(\lambda V\rho_L) = \alpha\left(\frac{PL}{\sigma}\right)^{a_1}\left(\frac{\rho_V}{\rho_L}\right)^{a_2}\left(\frac{k\Delta T_S}{VL\rho_L\lambda}\right)^{a_3}\left(\frac{\mu}{VL\rho_L}\right)^{a_4}\left(\frac{C_p\Delta T_S}{\lambda}\right)^{a_5}$$

which can be further simplified as

$$Q/A = \alpha' V^{b_1} P^{b_2} \Delta T_S{}^{b_3} \lambda^{b_4} \rho_L{}^{b_5} \rho_V{}^{b_6} \sigma^{b_7} k^{b_8} \mu^{b_9} C_p{}^{b_{10}}$$

Because the last seven variables are physical properties of the fluid which depend on the liquid temperature, we can write:

$$Q/A = \alpha' V^{b_1} P^{b_2} \Delta T_S{}^{b_3} f(T_L)$$

where $f(T_L)$ is the function of liquid temperature, representing the values of the last seven groups. Assuming $f(T_L) = \beta T_L{}^{b_4}$, then the equation becomes

$$Q/A = \alpha'' V^{b_1} P^{b_2} \Delta T_S{}^{b_3} T_L{}^{b_4}$$

(II) Vapor Pressure Correlation and Liquid Temperature - In order to calculate the liquid temperature and the physical properties of water, we have to calculate the vapor pressure of the water. For the operating range of our experimental data, the equation is

$$\log_{10} P = 6.21 - \frac{2949.4}{T_{sat}+373.1}$$

where

$$P = \text{pressure, psia}$$
$$T_{sat} = \text{saturation temperature, °F}$$

hence

$$T_L = T_{sat} - \Delta T_{sub}$$

$$= \left[\frac{2949.4}{6.21-\log_{10} P} - 373.1\right] - \Delta T_{sub}$$

where

$$T = \text{bulk liquid temperature, °F}$$
$$\Delta T_{sub} = \text{bulk subcooling, °F}$$

Because the liquid temperature is so important in the final correlation, we have to justify the above equation. The error is almost negligible as shown in Appendix A.

(III) Equations for Physical Properties of Water - The temperature or pressure dependency of the physical properties of water are given by the following equations. These equations were obtained from E. J. Thorgerson.[2]

$$\lambda = (1071.5-0.33172T_{sat}-0.000688T_{sat}^2)\text{x}2.205\text{x}1.055$$

$$\mu = (11.273-.14506T_L+0.00060541T_L^2)0.36$$

$$k = (560.95+2.0863T_L-0.008869T_L^2)/10^6$$

$$C_p = 4.1868-5.4585\text{x}10^{-4}T_L+8.2318\text{x}10^{-6}T_L^2$$

$$\rho_L = (1.0038-1.7795\text{x}10^{-4}T_L-2.7752\text{x}10^{-6}T_L^2)10^3$$

$$\rho_V = 1/(447.9-4.1457T_{sat}+.013247T_{sat}^2-\frac{1.4439}{10^5}T_{sat}^3)$$

$$/(0.02832\text{x}2.205)$$

$$\sigma = (75.64-0.1391T_L-0.0003T_L^2)1.0197\text{x}10^{-4}$$

where

T_{sat} - saturation temperature, °F

T_L - liquid temperature, °C

λ - latent heat of vaporization, $\frac{\text{kjoul}}{\text{kg}}$

μ - viscosity, $\frac{\text{kg}}{\text{m hr}}$

k - thermal conductivity, $\frac{\text{kjoul}}{\text{m °C sec}}$

C_p - specific heat, $\frac{\text{kjoul}}{\text{kg °C}}$

ρ_L - density of liquid, $\frac{\text{kg}}{\text{m}^3}$

ρ_V - density of vapor, kg/m³

σ - surface tension, kg_f/m

(IV) Least Square Method

From the previous equations, we have

$$\ln\left(\frac{Q/A}{\lambda V \rho_L}\right) = \ln\alpha + a_1 \ln\left(\frac{PL}{\sigma}\right) + a_2 \ln\left(\frac{\rho_V}{\rho_L}\right) + a_3 \ln\left(\frac{k\Delta T_S}{VL\rho_L\lambda}\right)$$

$$+ a_4 \ln\left(\frac{\mu}{VL\rho_L}\right) + a_5 \ln\left(\frac{C_p \Delta T_S}{\lambda}\right)$$

or $Y = C_1 + a_1 X_1\ a_2 X_2 + a_3 X_3 + a_4 X_4 + a_5 X_5$

Similarly

$$\ln\frac{Q}{A} = \ln\alpha'' + b_1 \ln V + b_2 \ln P + b_3 \ln \Delta T_S + b_4 \ln T_L$$

or $Y = C_2 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4$

The deviation is

DEV = Y(calc.)-Y(exp.)

The sum of deviation square is

$$\Sigma(\text{DEV})^2 = \sum_{i=1}^{n} (Y(\text{calc.}) - Y(\text{exp.}))^2$$

All these constant coefficients and exponents were determined using the library least squares computer program.

(V) Accuracy and Comparison - The final correlations as shown in the Summary are compared with the following correlations: Mirshak, Durant, Towell correlation.(3)

$$Q/A = 0.266(1+0.0365V)(1+0.00914\Delta T_s)(1+0.0131P)$$

G. E. Myers proposed correlation.(4)

$$Q/A = 0.1172(G\text{x}10^{-6})^{0.388}(\Delta T_{so})^{0.859}(D)^{-0.318}(P)^{0.081}$$

D. H. Knoebel correlation.(5)

$$Q/A = 0.08533(1+0.0515V)(1+0.124\Delta T_s)$$

The comparison is shown in the following table.

AVERAGE VALUES OF ABSOLUTE PERCENTAGE DEVIATION OF THE EXISTING COMPANY CORRELATIONS

Correlation	Whole Range 4-72.0°F 246 Points	High Subcool >25°F 206 Points	Low Subcool <25°F 40 Points
Mirshak, Durant, Towell	12.71	11.45	19.18
G. E. Myers	13.67	12.76	18.35
D. H. Knoebel	8.31	4.11	29.92
N. H. Chen			
Liquid Temperature	4.59 (I)	3.51 (III)	5.12 (V)
Physical Property	7.68 (II)	3.48 (IV)	4.73 (VI)

DISCUSSION

1. Equation I is recommended because it can be used for wider range than Equations III to VI even though the absolute average percentage deviation is somewhat higher than the corresponding value for high subcooling. Obviously Equation II derived using dimensionless groups is not as good as Equation I. The absolute average percentage deviation of Equation II is larger than that of Equation I because there are possible errors in the equations used to estimate the physical properties of water which were used to arrive at Equation II. Another advantage in recommending Equation I is that it is simpler than Equation II. However, Equation II has the merit that when other fluids are used in the correlation, it can be transformed to a more generalized equation more easily than Equation I. In other words, when many fluids are used, the representation of the correlating variables by the physical properties is more accurate than by a single parameter.

2. In the present analysis, the liquid temperature is used as the correlating variable in Equation I. To arrive at the best possible correlation, this temperature should be very accurate because the correlation shows that the burnout heat flux varies inversely as the 4.687 power of the liquid temperature.

3. The comparison of the proposed equations with existing previous correlations is very approximate because, with the exception of the Knoebel correlation, they were derived from different experimental data. The experimental conditions were more varied and experimental errors were larger.

RECOMMENDATIONS

The following recommendations are suggested for future work:

1. Change the configuration of experimental apparatus.

2. Use heavy water and other fluids.

3. Theoretical study.

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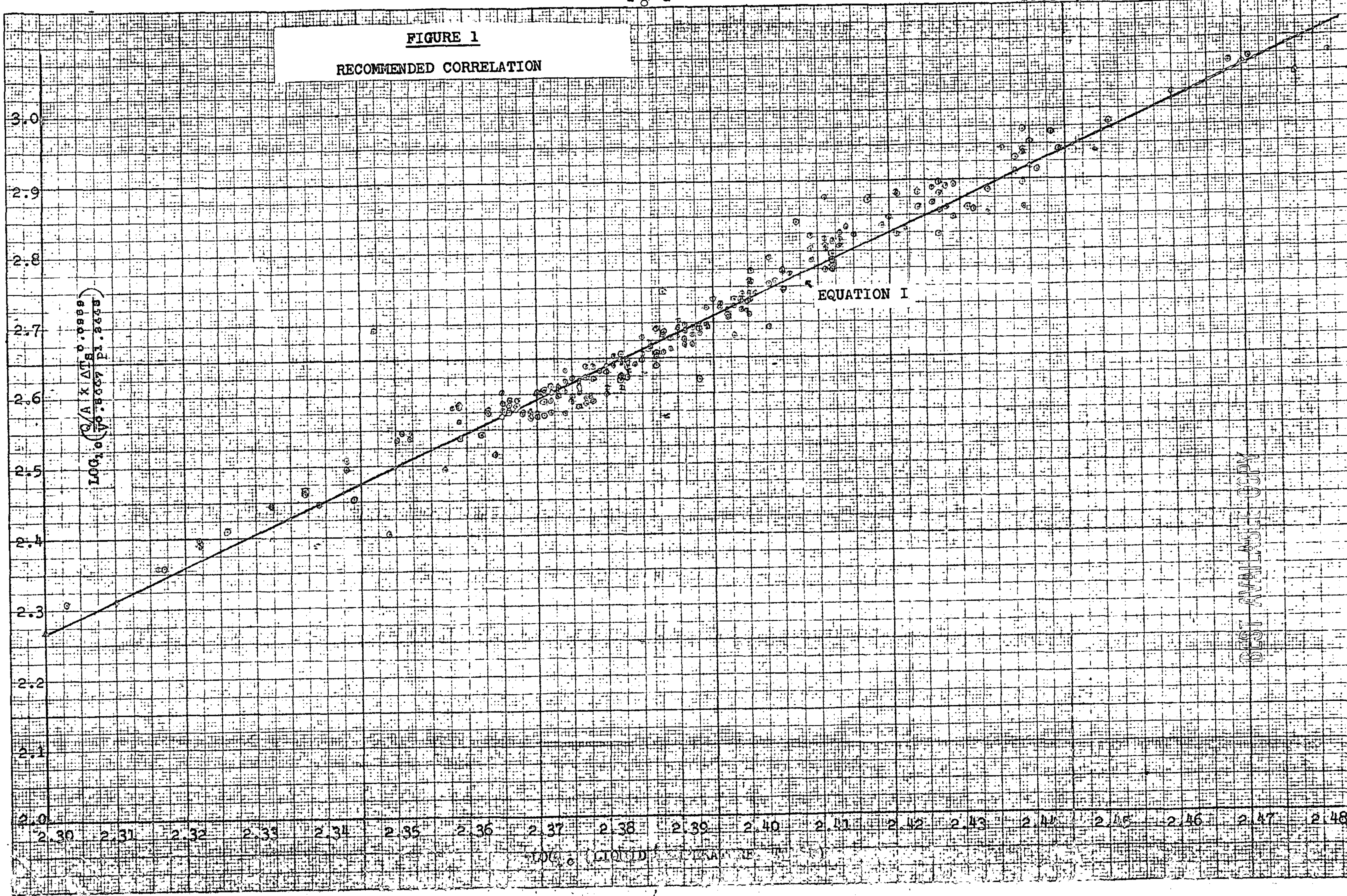

FIGURE 1

RECOMMENDED CORRELATION

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APPENDIX A

ACCURACY OF VAPOR PRESSURE CORRELATION

The following computer program was used to calculate the constants in the Antoine Equation for the vapor pressure of water. The experimental values were from Keenan and Keyes.

```
C     VAPOR PRESSURES BY ANTOINE EQUATION
      DIMENSION PCAL(1000),PSIA(1000),TF(1000),DSQ(1000),ERR(1000)
      CALL SETBTF
      CALL EFTM(10)
   88 CONTINUE
      READ(5,3) N,AA,BB,CC
    3 FORMAT(I5,3F15.4)
      READ(5,2)(PSIA(I),TF(I),I=1,N)
    2 FORMAT(2F15.5)
      DO 4 I=1,N
      PCAL(I)=EXP(2.302585*(AA+BB/(TF(I)+CC)))
      ERR(I)=100.0*(PSIA(I)-PCAL(I))/PSIA(I)
      DSQ(I)=(PSIA(I)-PCAL(I))**2
    4 CONTINUE
      SUME=0
      SDSQ=0
      DO 70 I=1,N
      SUME=SUME+ERR(I)
      SDSQ=SDSQ+DSQ(I)
   70 CONTINUE
      AERR=SUME/N
      SY=SQRT(SDSQ/(N-2))
      AN=N
      SERR=SY/SQRT(AN)
      WRITE(6,10)(TF(I),PSIA(I),PCAL(I),ERR(I),I=1,N)
   10 FORMAT(8X, 'T(F)',10X, 'PSIA',9X, 'P(CAL)',10X, '% ERR'//(4(1PE
     115.4)))
      WRITE(6,20) AERR,SY,SERR
   20 FORMAT(' AERR=',E20.5,',SY =',E20.5,',SERR =',E20.5)
      GO TO 88
   99 STOP
      END
```

The following equation was calculated from the above code:

$$\log_{10} P = 6.21 - \frac{2949.4}{T+373.1}$$

where

P = pressure, psia

T = temperature, °F

The following table presents a comparison of the steam table values and those calculated from the above equation:

TABLE A-1

T(F)	PSIA (Steam Table)	P(CAL)	% ERR
2.2796E 02	2.0000E 01	2.0001E 01	-4.9591E-03
2.5033E 02	3.0000E 01	3.0001E 01	-1.9328E-03
2.6725E 02	4.0000E 01	4.0007E 01	-1.8349E-02
2.8101E 02	5.0000E 01	5.0007E 01	-1.4069E-02
2.9271E 02	6.0000E 01	6.0016E 01	-2.7415E-02
3.0292E 02	7.0000E 01	7.0012E 01	-1.7722E-02
3.1203E 02	8.0000E 01	8.0018E 01	-2.2602E-02
3.2027E 02	9.0000E 01	9.0022E 01	-2.4465E-02
3.2781E 02	1.0000E 02	1.0003E 02	-2.5085E-02
3.3477E 02	1.1000E 02	1.1002E 02	-2.1085E-02
3.4125E 02	1.2000E 02	1.2003E 02	-2.3282E-02

AERR= -0.18270E-01,SY = 0.19116E-01,SERR = 0.57636E-02

AERR = average error

SY = standard error

SERR = average absolute deviation